Published in IEEE Transactions on Plasma Science, 2018, **DOI:** 10.1109/TPS.2018.2856306

Breakdown Characteristics of Plasma Closing Switch Filled with Air, N_2, CO_2 and Ar/O_2

Y. Yao, I. Timoshkin, *Senior Member, IEEE*, S. J. MacGregor, *Senior Member, IEEE*, M. P. Wilson, *Member, IEEE*, M. J. Given, *Senior Member, IEEE*, T. Wang

***Abstract*— One of the critical components of high energy density pulsed power systems used to generate short high-voltage and high-power impulses is gas-filled plasma closing switch. In recent years significant research efforts have been aimed at finding environmentally friendly gases which can be used in the plasma closing switches, and several gases including dry air, nitrogen, carbon dioxide, argon and their mixtures have been considered as potentially suitable working fluids in such switches. However, the lack of knowledge of the breakdown characteristics of complex switching topologies filled with these gases limits their practical applications. Therefore, further investigation of the breakdown performance of plasma closing switches is required, in order to establish their applicability for practical use in high voltage pulsed power systems. The present paper reports on the investigation of the breakdown characteristics of a triggered plasma closing switch topology with corona discharge electrodes. The self-breakdown voltage of the switch, variation in the self-breakdown voltage, time to breakdown, and jitter have been obtained for the switch filled with "Zero Grade" air, N_2, CO_2 and an Ar/O_2 mixture up to a pressure of 10 bar (abs). It was shown that the switch can provide a stable breakdown performance with jitter as low as ~1 ns.**

***Index Terms*— pulsed power systems, gas filled plasma closing switch, nanosecond jitter, air, nitrogen, carbon dioxide, argon/oxygen gases mixture, dielectric behavior.**

I. Introduction

High voltage gas-filled plasma closing switches (PCS) are widely used in power and pulsed power systems due to their capability to operate in over voltage and current ranges, their ability to cope with high *dV/dt* and *dI/dt* values, and to provide short switching time with low jitter when operated in a triggered mode, [1], [2]. Although solid state switching technology continues to gain popularity as a potential replacement for the gas-filled PCS's in some pulsed power systems and applications, the plasma closing switches remain important components for different practical high voltage and high power impulsive systems due to their robustness, exceptional operational capabilities and characteristics and relatively low cost. Hence, researchers and engineers continue to invest significant efforts in the design and development of novel switch topologies in order to improve their breakdown performance and switching characteristics.

One of the issues currently being addressed by pulsed power researchers and engineers involved in the design, manufacture and exploitation of pulsed power systems with PCS's is the use of environmentally friendly gases as working fluids in PCS's. Traditionally, SF_6 was used in the gas switching systems as this gas provides high breakdown strength, and high recovery capabilities. However, due to environmental concerns there is a significant interest in finding a gas/gas mixture that can be used in PCS's instead of SF_6, [3-8].

Improvement of the operating characteristics of PCS's is another area of interest for the pulsed power community. Gas-filled plasma switches with higher breakdown voltage, lower standard deviation in the self-breakdown voltage, and lower jitter are in high demand for different practical pulsed power applications, [9-12], [21]. For example, papers [13 - 15] report on the development and study of a PCS that was triggered by plasma ejected into the gas gap from the triggering electrode. This topology was designed with the aim of achieving multi-channelling and a wider triggering range, the switch was filled with N_2 and SF_6. However, the plasma jet-triggered switch demonstrated a long delay time, in the 10's of μs range, also there is no published information on the jitter of the switch. Papers [16] and [20] reported on investigation of operational parameters of a high-pressure switch, operated at pressures up to ~22 bar, filled with dry air, N_2, SF_6, H_2 and N_2-SF_6 and N_2-H_2 gas mixtures. It was shown that a nitrogen-filled switch demonstrated the lowest (sub-ns) jitter.

Another important aspect currently being addressed is the development of compact PCS's that will facilitate reduced footprint of practical pulsed power systems. For example, [12] describes the development of a multi-electrode gas-filled PCS with a high operating voltage, up to 1 MV, and the low standard deviation in a breakdown voltage, 2-3%. However, this switch was filled with SF_6.

To achieve desirable operational performance in specific pulsed power applications, complex plasma switching topologies with corona discharge electrodes can be used. Although a number of publications have reported on the development of corona-stabilised PCS's that operate in an air environment, [17-19], the breakdown parameters of such

The manuscript has been received on 29 December 2017, in the final form on XX Month 2018.

Y. Yao, I. V. Timoshkin, S. J. MacGregor, M. P. Wilson, M. J. Given, and T. Wang are with the Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XW, U.K. (e-mail: yuan.yao.101@strath.ac.uk; igor.timoshkin@strath.ac.uk; scott.macgregor@strath.ac.uk; mark.p.wilson@strath.ac.uk; m.given@strath.ac.uk; tao.wang@strath.ac.uk).

switches still require further optimisation and other environmentally friendly gases should be investigated in order to find the optimal solution for different practical applications.

The present work is focused on the development of a two-stage triggered gas-filled PCS with corona discharge electrodes, which can provide a low spread in the self-breakdown voltage and low jitter when filled with environmentally-friendly gases. The environmentally friendly gases chosen for investigation in this work are the electronegative fluids (“Zero grade” air, CO_2, and 90%/10% Ar/O_2 mixture) and N_2 which has very low electron affinity. All gases were obtained from an industrial gas supplier, BOC, a member of the Linde Group. “Zero grade” air was a 79%/21% N_2/O_2 mixture (N_2 purity 99.998%, O_2 purity 99.6%); CO_2 had 99.8% purity, N_2 had 99.998% purity; and the 90%/10% Ar/O_2 mixture consisted of Ar with 99.999% purity and O_2 with 99.6% purity.

The self-breakdown and triggered breakdown characteristics of the developed PCS have been investigated over a wide range of gas pressures, 1-10 bar (absolute) in order to establish phenomenological relationships between the operating voltage, standard deviation in the self-breakdown voltage, pre-breakdown delay time and jitter and the gas pressure in the switch. These phenomenological relationships will help in further optimisation and development of PCS’s filled with environmentally friendly gases.

II. EXPERIMENTAL

A. Plasma Closing Switch with Corona electrodes

A dedicated two-stage PCS with a highly divergent electric field has been designed and constructed, the cross section of the switch is shown in Fig. 1.

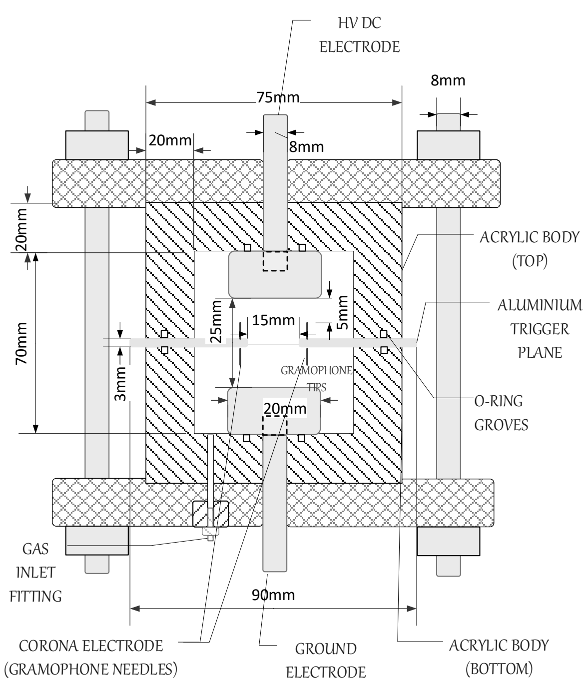


Fig. 1. A cross-section of the developed PCS with 4 needle electrodes on each side of the central plate. Needles and upper and lower plane electrodes form 5 mm inter-electrode gaps.

The upper and lower parts of the switch body were made of clear acrylic (Perspex) cylinders with an internal diameter of 35 mm and external diameter of 75 mm, and the total height of the switch was 70 mm. The thickness of the acrylic cylinders was chosen to ensure that this PCS could withstand operating pressures up to 10 bar (abs). Two cylindrical stainless-steel electrodes located at the top and the bottom of the switch have flat circular surfaces, 20 mm in diameter. An aluminium trigger ring electrode with an internal aperture of 20 mm was located between the two acrylic cylinders, and located symmetrically between the two main (plane) electrodes. Four gramophone needle electrodes were symmetrically mounted around the internal aperture on each side of the trigger electrode, providing a highly non-uniform electrical field distribution in order to generate pre-breakdown non-thermal plasma (corona) discharges within the switch. The distance between the tips of these needles and the plane electrodes was 5 mm in both, upper and lower gaps.

B. Experimental Arrangement

The experimental system used to study the breakdown characteristics of the gas-filled PCS is composed of a gas control and distribution system, the PCS shown in Fig.1, a high voltage dc power supply and a PC-based control system to provide both positive and negative voltages with a specific ramp rate, a trigger impulsive generator, and high voltage diagnostic equipment (HV probes and a digitising oscilloscope). The gas control system includes the gas distribution board, a rotary vacuum pump to evacuate the switch prior to filling with gas under test, and a digital pressure controller, Alicat PC-1500PSIG-D, to set and control the pressure in the switch.

A diagram of the experimental set-up used for the self-breakdown and triggered breakdown voltage measurements is shown in Fig. 2. A Glassman high voltage dc power supply was used to stress the upper plane electrode via a 1 MΩ charging resistor. The voltage output from the power supply was controlled by a PC via an RS 232 interface.

For the self-breakdown voltage measurements, the upper electrode was stressed with both positive and negative voltages; the ramp-rate of the applied voltage stress was 2 kV/s. A North Star PVM-5 high voltage probe (with the following nominal characteristics as provided in [22]: 80 MHz bandwidth, 400 MΩ input resistance, and 12 pF input capacitance) was used to monitor the voltage across the switch. As shown in Fig 2, the PVM-5 probe was connected to the upper plane HV electrode. The central electrode of the switch with the corona needles was at a floating potential, thus the field at the tips of these corona needles was a space charge influenced field defined by corona activity in the gas.

For the triggered breakdown measurements, the central electrode was connected to an inverting Blumlein topology which was charged by Glassman high voltage dc power supply, via a 1MΩ charging resistor. This trigger generator produces negative square impulses with duration of 250 ns and peak magnitude of 30 kV. The upper plane electrode was constantly stressed with a positive dc voltage, via a 1 MΩ charging resistor. A negative trigger impulse was applied to the central trigger electrode. The trigger impulse voltage waveforms were monitored using a Tektronix P6015A high-voltage probe connected to the central trigger plane of the switch. The P6015A probe has the following nominal characteristics as provided in [23]: 75 MHz bandwidth, 100 MΩ input resistance, and 3 pF input capacitance). The voltage signals were monitored using a Tektronix TDS 3050 digitising oscilloscope (500 MHz bandwidth, 5 GS/s sampling rate).

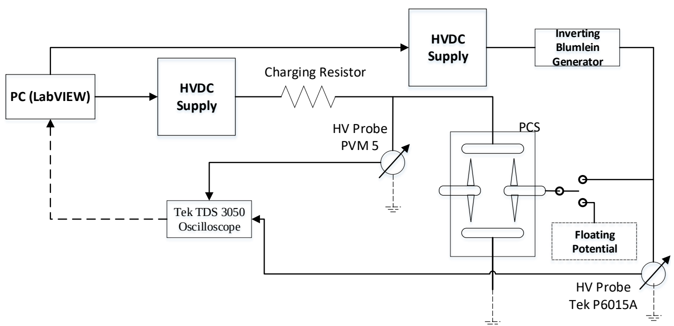


Fig. 2. Schematic diagram of the experimental set-up used for self-breakdown measurements (the central electrode of the PCS is at a floating potential) and for impulsive breakdown characteristics (the central electrode of the PCS is connected to the Blumlein trigger generator).

C. Self-breakdown Voltages

Self-breakdown voltages were measured for all gases over the pressure range from 1 to 10 bar in 1 bar increments. The upper plane electrode was stressed with both positive and negative voltages. In each test the self-breakdown voltage was recorded for 30 consecutive breakdown events, and the average value and its standard deviation were calculated.

The obtained average self-breakdown voltage, V_{br}, for all tested gases is plotted in Fig. 3 as a function of the gas pressure in the switch, for both positive and negative energisation. Each point on the graph shows a mean value of 30 breakdown voltages, and the error bars show the standard deviation for each set of measurements conducted using a fresh portion of tested gas or gas mixture. As can be seen from Fig. 3, there is no substantial difference between positive and negative self-breakdown voltages for all tested gases. This is due to the gramophone needle electrodes mounted on each side of the centre floating electrode and protruding into both gaps, located between the main electrodes of the switch. If the HV electrode is at a positive polarity, the needles on the central electrode in the upper gap will be at a lower potential than the HV electrode that they face, therefore the space charge developed by corona discharge in the upper gap will lead to an increase in the breakdown strength in this gap; while in the lower gap the needles will be at a higher potential than the ground electrode that they face and the breakdown strength of this gap will be lower than that of the upper gap. When the HV electrode is at a negative potential the needles in the upper gap will be at a potential higher than the HV electrode while the needles in the lower gap will be at a potential lower than the ground electrode increasing the breakdown strength of the lower gap as compared with the upper gap. Due to the symmetry of the geometry there will always be one gap with a common lower breakdown strength, independent of polarity, which will dominate the breakdown behaviour of the system. Therefore, the self-breakdown voltage is almost the same in both, positive and negative energisation modes.

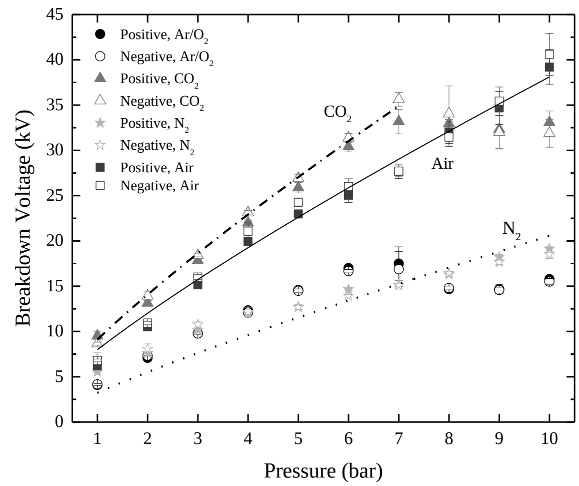


Fig. 3. Self-breakdown voltage, V_{br}, vs gas pressure. Each symbol is an average value of 30 measurements: squares, air; stars, N_2; triangles, CO_2; circles, 90%/10% Ar/O_2. Solid symbols, positive energisation; open symbols, negative energization. V_{br} obtained by equation (1): solid line, air; dash-dotted line, CO_2; dotted line, N_2.

The measured self-breakdown voltage for each gas was fitted with an analytical line, $V_{br}(p)$, obtained by Equation 1 which is based on the Townsend breakdown theory:

$$V_{br} = \frac{\beta B\, pd}{ln(A\, pd) - ln(G)} \tag{1}$$

where p is the gas pressure, d is the inter-electrode distance, the constants A and B describe the primary ionisation coefficient; G is a gain coefficient (in Townsend theory, G is a function of the secondary ionisation coefficient). The coefficient β is the ratio between the uniform field in a parallel-plane topology and the maximum Laplacian field at the point electrode in a point-plane topology. In the present work this ratio was obtained by modelling the point-plane topology in Electro electrostatic software and found to be $\beta \sim 1/11$ (for d = 5 mm and for a needle electrode with radius of 0.04 mm).

The Meek streamer onset condition, exp (G) ~ 10^8, defines the gain coefficient for spark breakdown in parallel-plane topologies, $G \approx 18.2$, [24]. However, in the case of breakdown in a strongly non-uniform field topology, ionisation takes place only in the vicinity of the sharp electrode and the calculated value of G is unrealistically high: in [24] the gain coefficient obtained for the spark breakdown voltage in air in the rod-plane topology is in the range from ~ 100 to ~ 340 ($ln(G)$ from 4.6 to 5.8) for the conditions when the spark breakdown voltage is higher than the corona ignition voltage. Thus, in strongly non-uniform fields, the analytically obtained G provides an unrealistically high number of electrons in the avalanche and cannot be used for estimation of the secondary ionisation coefficient. As suggested in [24], two main reasons for such overestimation are: branching of streamers and space charge distortion of the field in the vicinity of the sharp electrode.

However, for the purpose of comparison and to provide an analytical fitting that can be used for practical purposes, the experimentally obtained V_{br} values were fitted with Equation 1 using the best fit procedure in Origin Pro graphing software. In the case of air and N_2 the fitting was conducted over the whole pressure range; in the case of CO_2, the fitting was conducted for the data from 1 bar up to 7 bar, the pressure range over which the maximum breakdown voltage was achieved. The parameter *ln(G)* was a fitting parameter, and the values of *A* and *B* were taken from [25]. A 5 mm inter-electrode distance was used in the fitting procedure assuming that all breakdown events were initiated in both, upper and lower, gaps of the switch. The fitting lines are shown in Figure 3, and the obtained values of *ln(G)* with their standard errors are given in Table 1. The experimental values of V_{br} for the 90%/10% Ar/O_2 mixture were not fitted with Equation 1, as no values of *A* and *B* are available for this gas mixture.

TABLE I
COEFFICIENTS *A*, *B*, AND FITTING PARAMETER *ln*(*G*)

Gas	*A* ($\times10^3$, $(cm\cdot bar)^{-1}$)	*B* ($kV/(cm\cdot bar)$)	*ln(G)*
Air	11.0	268.5	7.0±0.1
N_2	6.7	209	5.8±0.1
CO_2	15.2	354.2	7.2±0.1

The present study is focused on the development and characterisation of the PCS which operates when filled with environmentally friendly gases only, therefore SF_6 was not considered in this work. However, previously published data can be used to compare the behaviour of the breakdown voltage of SF_6 with that of other gases. In [26], for example, the spark breakdown voltage for different gases - including SF_6 and air - was obtained as a function of the gas pressure in a point - sphere electrode topology with the field non-uniformity coefficient, $\beta \sim 1/5$. The positive breakdown voltage of SF_6 has its maximum value, $V_{br\text{-}max}$, at a pressure of ~ 5.5 bar; at ~ 6.5 bar, V_{br} drops by ~ 38% from its peak value and becomes only ~ 2-fold higher than that of air. A relationship between the maximum breakdown voltage, the gas pressure and the inter-electrode distance in SF_6 is provided in [27]: it was found that $V_{br\text{-}max}/(pd)$ = (30-40) kV/(cm·bar) - this relationship depends on the field non-uniformity factor, and is valid for distances d = 0.13-15 cm. As reported in [27], the functional behaviour of the breakdown voltage of air-filled non-uniform topologies is similar to that of SF_6–filled gaps. However, the monotonic increase of V_{br} with the gas pressure (until its maximum) is observed in air over a wider pressure range than in SF_6. This could be an operational advantage of air-filled PCSs, notwithstanding the lower breakdown voltage of air as compared with SF_6.

Generally, the obtained self-breakdown voltages show that the tested gases can be combined into two distinct groups: air and CO_2 demonstrate higher self-breakdown voltages in the developed switching topology as compared with N_2 and the Ar/O_2 mixture. For pressures up to 7 bar CO_2 provided higher self-breakdown voltages than all other tested gases, while N_2 and the Ar/O_2 mixture provided the lowest self-breakdown voltages. However, the self-breakdown voltage for CO_2 demonstrates a non-linear behaviour and starts to decrease for pressures above 7 bar. On the contrary, the breakdown voltage of air increases almost linearly with gas pressure and becomes higher than the self-breakdown voltage of CO_2 for pressures above 7 bar. V_{br} for the Ar/O_2 mixture also shows a non-linear behaviour, with a maximum V_{br} at 7 bar. Discussion of the potential physical mechanisms responsible for such non-linear behaviour of the breakdown voltage is given in Section IV.

Figs. 4(a) - (d) show the standard deviation in the self-breakdown voltage, σ_{Vbr}, for each tested gas (air, N_2, CO_2, and the 90%/10% Ar/O_2 mixture) as a function of the gas pressure in the switch. It was found that σ_{Vbr} in air and CO_2 are greater than those for the N_2 and Ar/O_2 mixture and σ_{Vbr} in air and CO_2 significantly increases with an increase in the pressure (Figs. 4(a), and (c)). Fig. 4(d) represents the standard deviation of the self-breakdown voltage for the switch filled with the Ar/O_2 mixture. For this gas mixture, σ_{Vbr} demonstrates a slight increase with an increase in the pressure. It should be noted that there is a significant increase in the standard deviation at 7 bar which could be potentially attributed to the change in the self-breakdown voltage behaviour at this pressure: $V_{br}(p)$ for the switch filled with the Ar/O_2 mixture reaches the maximum value at 7 bar and then drops at 8 bar, (Fig. 3). In the case of the N_2-filled switch, no distinct trend has been observed for the standard deviation in V_{br}.

Exponential function (2) has been fitted to the standard deviation data, σ_{Vbr}, shown in Fig. 4 using Origin Pro graphing software. Equation (2) describes the relationship between the standard deviation in the self-breakdown voltage, σ_{Vbr}, (kV) and the gas pressure, p (bar):

$$\sigma_{Vbr} = C\ exp(Dp) \qquad (2)$$

where C (kV) and D (bar^{-1}) are fitting coefficients obtained for both polarities of the applied voltage. These coefficients and the standard errors are given in Table II.

TABLE II
COEFFICIENTS *C* AND *D* FOR EQUATION (2)

Gas	*C* (kV)	*D* (bar^{-1})
Air	0.06 ± 0.01	0.36 ± 0.02
N_2	0.15 ± 0.05	0.07 ± 0.05
CO_2	0.13 ± 0.04	0.24 ± 0.04
Ar/O_2	0.06 ± 0.01	0.18 ± 0.03

The greater the coefficient *D* is, the faster the standard deviation rises with an increase in the gas pressure in the switch. According to Table II, N_2 provides the most consistent variation in the self-breakdown voltage.

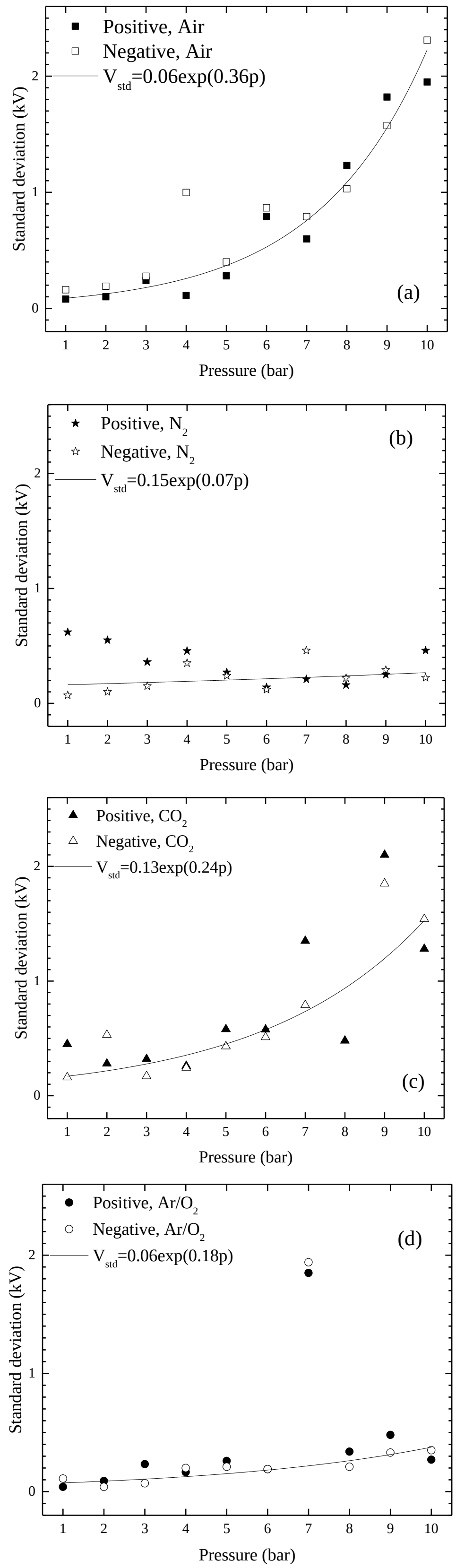


Fig. 4. Standard deviation in the self-breakdown voltage as a function of gas pressure. Solid symbols, positive energisation; open symbols, negative energisation. Standard deviation was calculated for 30 breakdown measurements for each gas pressure. (a), synthetic air; (b), N_2; (c), CO_2; (d), 90%/10% Ar/O_2.

D. *Triggered Operation of the Switch*

In the triggered mode of operation, the upper plane electrode of the switch was stressed with a positive dc voltage. Two stress levels were used in this study, 70% and 90% of the self-breakdown voltage. A negative trigger impulse with a magnitude of 30 kV was supplied to the central trigger electrode of the switch, (Figure 1): where the output from the inverting Blumlein inverting topology was connected to the central electrode of the switch).

Fig. 5 shows typical waveforms of the trigger impulse and the voltage across the main gap of the switch which collapses when switch is completely closed. Time to breakdown, t_{br}, is the time interval from the starting point of the trigger impulse to the moment of complete closure of the switch which is defined by the collapse of the dc voltage across the switch.

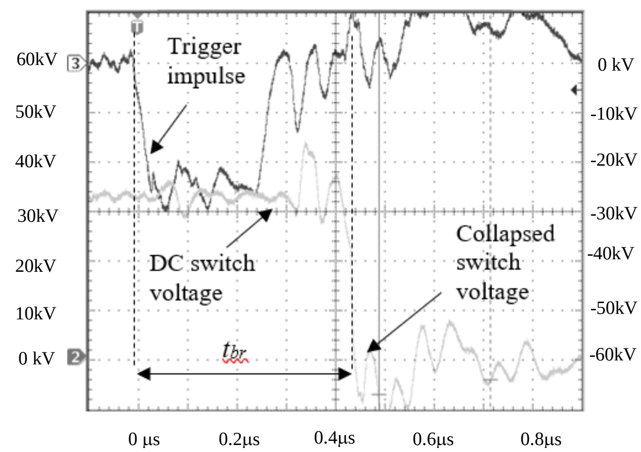
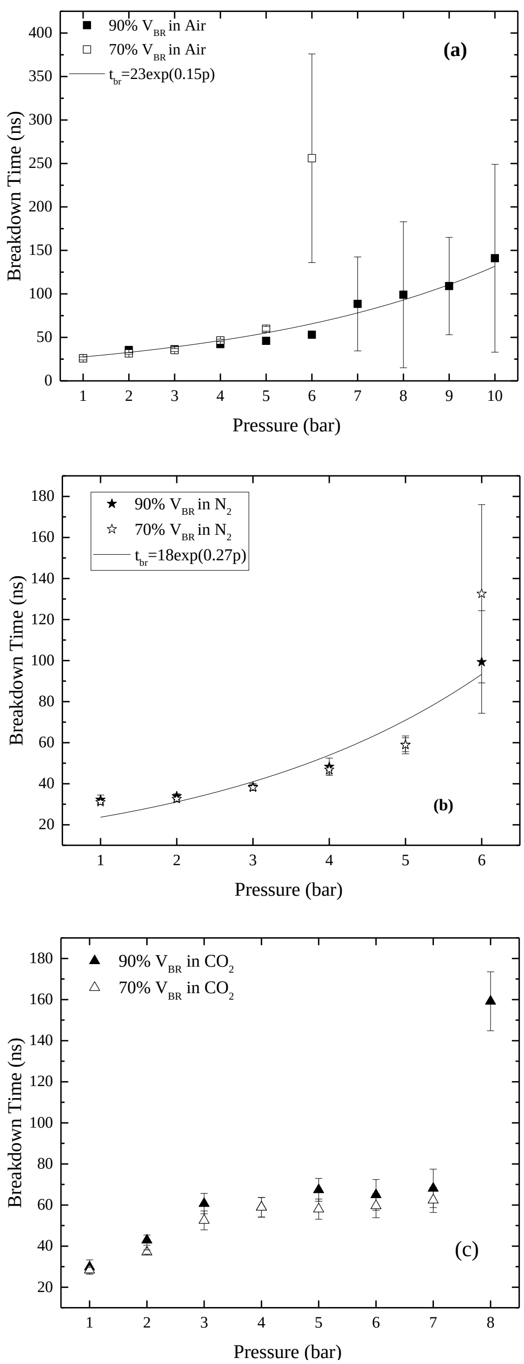


Fig. 5. Typical voltage waveforms: negative trigger impulse, positive dc stress across the switch which collapses when the switch is closed. The upper ground level (0 kV) on the right-hand *y*-axis is related to the negative trigger impulse, and the lower ground level on the left-hand *y*-axis is related to the positively stressed HV plane electrode. The time 0 µs is related to the start of the trigger impulse; t_{br} is time to breakdown.

In these series of tests, the triggered switch was filled with the same gases as for the self-breakdown voltage measurements (Section II-C): air, N_2, CO_2, and the Ar/O_2 mixture. Time to breakdown was measured for 20 consecutive breakdown events in each gas, and the average time to breakdown values and their standard deviations (jitter) were calculated. Figs. 6(a) - (d) show the time to breakdown as a function of the gas pressure.

When the switch was filled with air and stressed with 70% of the self-breakdown voltage, the time to breakdown increases sharply at 6 bar. This is the maximum pressure at which breakdown events were registered, no breakdowns were observed for air pressures above 6 bar at this energisation level. The time to breakdown at this maximum pressure showed the high standard deviation (jitter) which will be discussed in the next section. When the air-filled switch was stressed with 90% of its self-breakdown voltage, the breakdown events were observed over the whole pressure range, and the time to breakdown increases with an increase in the air pressure.

In the case of a N_2-filled switch, the time to breakdown also demonstrated continuous growth with an increase in the gas pressure for both, 70% and 90% self-breakdown energisation levels. The maximum pressure at which breakdown events were observed was 6 bar for both energisation levels, no breakdowns were observed for higher pressures. As in the case of air, both the time to breakdown and jitter increase significantly at the maximum operation pressure, 6 bar.



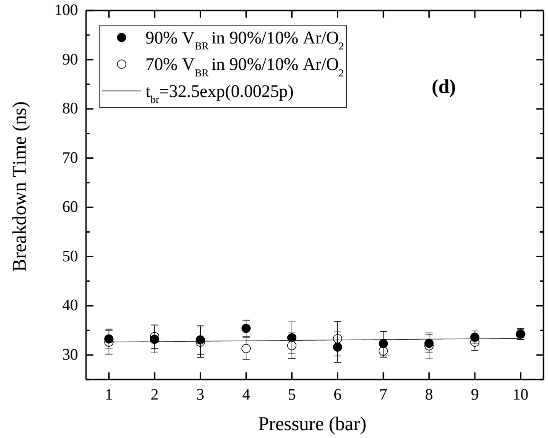


Fig. 6. Time to breakdown vs gas pressure for both 70% and 90% of the dc self-breakdown voltage applied across the switch as a dc stress voltage. (a), air; (b), N_2; (c), CO_2; (d), 90%/10% Ar/O_2. Each point is an average value of 20 measurements, error bars represent the standard deviation values.

Exponential function (3) was fitted to the time to breakdown data in air and N_2 using Origin Pro graphing software. Equation (3) describe the link between the time to breakdown, t_{br}, (ns) and the gas pressure, p (bar):

$$t_{br} = M\, exp(Np) \qquad (3)$$

where M (ns) and N (bar^{-1}) are fitting coefficients. These coefficients are given in Table III for each of the gases.

TABLE III
COEFFICIENTS M AND N FOR EQUATION (3)

Gas	M (ns)	N (bar^{-1})
Air	23 ± 9.7	0.15 ± 0.1
N_2	24 ± 1.3	0.17 ± 0.01
Ar/O_2	32.5 ± 0.74	0.0025 ± 0.003

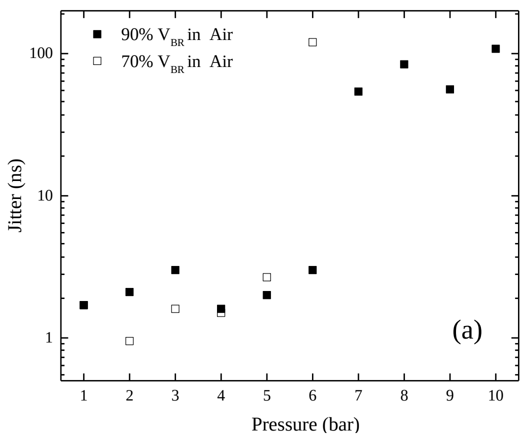
The breakdown time at the maximum operating pressure (for air and N_2) was excluded from this fitting procedure as the observed increase in the time to breakdown and jitter indicates unstable operation of the PCS.

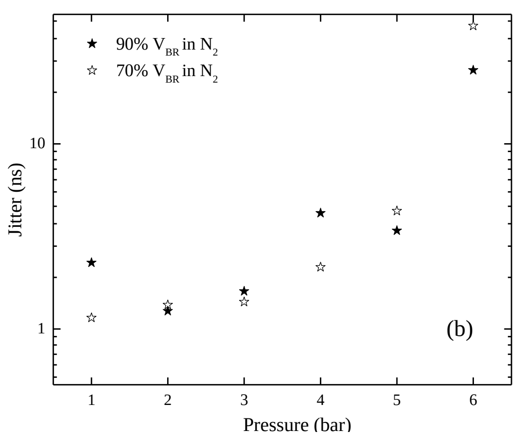
When the switch was filled with CO_2 and stressed with 90% of the self-breakdown voltage, the time to breakdown increased and saturated at ∽(60-67) ns for pressures 3-7 bar for both energisation levels and then increased sharply to ∽160 ns at 8 bar (for 90% self-breakdown energisation level). Again, this increase in the time to breakdown and jitter was observed at the maximum operating pressure, 8 bar: no breakdown events in CO_2 were observed for higher gas pressures. It was not possible to fit function (3) to the time to breakdown data in CO_2.

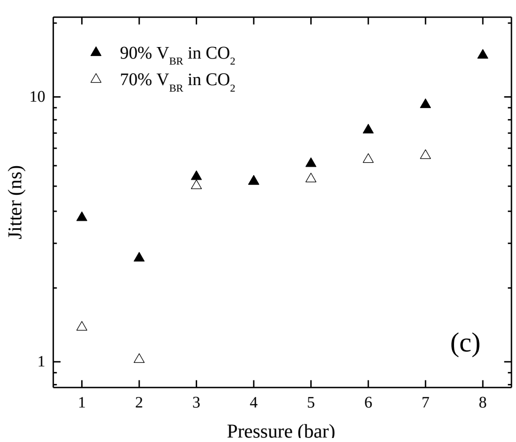
In the case of the Ar/O_2 mixture, breakdown events were observed over the full pressure range for both, 70% and 90% self-breakdown energisation levels. The time to breakdown varied slightly within this pressure range and remained ~ (30 - 35) ns for both energisation levels. Exponential function (3) was fitted to the time to breakdown data with a low power coefficient, $N = (2.5 \pm 3)\times10^{-3}$, (Table III).

Published in IEEE Transactions on Plasma Science, 2018, **DOI:** 10.1109/TPS.2018.2856306

In order to investigate jitter for the PCS filled with all tested gases, jitter as a function of the gas pressure in the switch was plotted in Fig.7. As can be seen from Fig. 7, in the cases of air, CO_2 and N_2, jitter increased with an increase in the gas pressure. When the switch was filled with air, jitter varies in the range from ~1 ns to ~3.8 ns for pressures up to 5 bar for both energisation levels and then rose sharply to ~ (54 - 108) ns for pressures >7 bar (for the 90% energisation level). For the 70% energisation level jitter increased to ~120 ns for 6 bar which was the highest operating pressure for air at this energisation level.







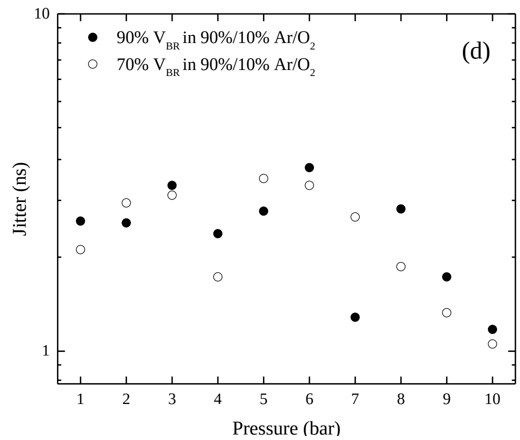


Fig. 7. Jitter for the PCS as a function of gas pressure for both 70% and 90% of the dc self-breakdown voltage applied across the switch as a dc stress voltage. (a), air; (b), N_2; (c), CO_2; (d), 90%/10% Ar/O_2.

In the case of N_2 and CO_2, jitter increases from a few ns at low pressures up to ~14 ns for CO_2 (at 8 bar, the 90% energisation level) and up to a few 10's ns for N_2 at 6 bar. These pressures, 8 bar and 6 bar, were the maximum operating pressures for CO_2 and N_2 respectively. When the switch was filled with the Ar/O_2 mixture the jitter remained within the range from ~1.6 ns to ~3.5 ns for pressures up to 6 bar for both energisation levels, and demonstrated a decreasing tendency for pressures > 6 bar reaching the values of ~1.2 ns and ~1.1 ns at 10 bar for the 70% and 90% energisation levels respectively.

III. Weibull Statistical Analysis

The obtained time to breakdown data were subjected to a Weibull statistical analysis, [28], [29], in order to compare the reliability of the switch when filled with different gases. A three-parameter Weibull distribution, [30], [31], used in the present analysis is described by the cumulative distribution function of the probability of breakdown events, $F(t_{br})$:

$$F(t_{br}) = 1 - exp\left\{-\left(\frac{t_{br}-t_0}{\alpha}\right)^{\beta}\right\};\ \ t_{br} \geq t_0 \quad (4)$$

where t_{br} is the time to breakdown; α is the scale parameter - the characteristic time to breakdown; β is the shape parameter which defines the slope of the regressed line in the Weibull plot; t_0 is the location parameter - the waiting time which is related to the minimum time to breakdown.

As an example, Fig. 8, shows the Weibull distribution graph for the time to breakdown when the switch was filled with CO_2 at 1 bar, and stressed with 70% of the self-breakdown voltage. This statistical analysis was performed using Origin Pro graphing software which provided the Weibull coefficients, α, β, and t_0; and calculated both, upper and lower, 95% confidence intervals. The Weibull statistical analysis was performed using the data for all gases, pressures and energisation levels.

Published in IEEE Transactions on Plasma Science, 2018, **DOI:** 10.1109/TPS.2018.2856306

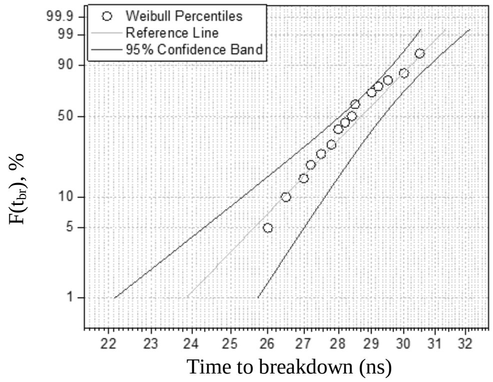


Fig. 8. $F(t_{br})$ for the PCS filled with CO_2 at 1 bar and stressed with 70% of the self-breakdown voltage.

Figs. 9 - 11 show the obtained Weibull parameters for the switch filled with air, N_2, CO_2, and Ar/O_2 for each gas pressure in the range from 1 bar to 10 bar, and for two energisation levels, 70% and 90% of the self-breakdown voltage.

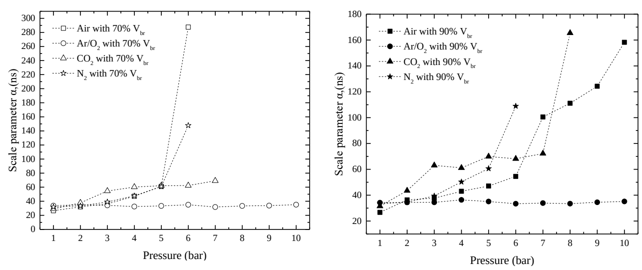


Fig. 9. The scale parameter as functions of the gas pressure for both 70% (open symbols) and 90% (solid symbols) of the dc self-breakdown voltage. Connection dashed lines are provided for visual guidance only.

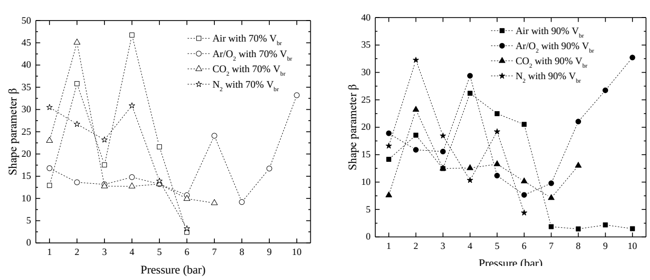


Fig. 10. The shape parameter as functions of the gas pressure for both 70% (open symbols) and 90% (solid symbols) of the dc self-breakdown voltage. Connection dashed lines are provided for visual guidance only.

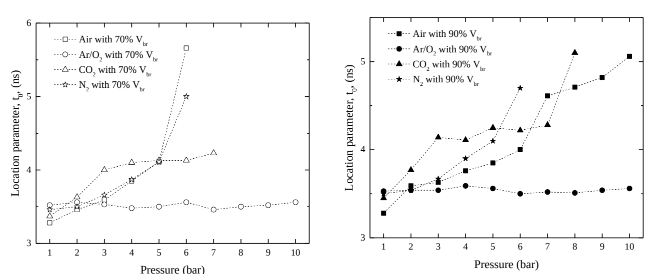


Fig. 11. The location parameter as functions of the gas pressure for both 70% (open symbols) and 90% (solid symbols) of the dc self-breakdown voltage. Connection dashed lines are provided for visual guidance only.

It was found that the scale parameter (the characteristic time to breakdown), α, increases as the gas pressure in the switch increases for all tested gases except for the Ar/O_2 mixture, Fig.9. For N_2 and CO_2 α increases at the maximum operating pressure, which is the maximum pressure at which breakdown events were achieved in these gases.

The shape parameter, β, defines the slope of the cumulative distribution function (4) in the probability plot. $\beta > 1$ indicate that the switch has an increasing rate of breakdown events with the time to breakdown. For all gases at all tested pressures (except for air at pressures >7 bar), the shape parameter β is greater than 3.7, Fig.10, thus the probability distribution function is negatively skewed indicating a higher probability of breakdown events with longer time to breakdown. In the case of the Ar/O_2-filled switch the shape parameter, β, demonstrates an increasing tendency for gas pressures above 7 bar (for 90% energisation level). However, in the case of air, for pressures > 7 bar (and the same energisation level), the values of β tend to 1. If $\beta = 1$, the reliability of the switch remains the same during its operation, i.e. the rate of breakdown events doesn't depend on the time to breakdown.

The location parameter, t_0, is related to the minimum time to breakdown in the PCS. For air, CO_2, and N_2 the location parameter (waiting time) increases with an increase in the gas pressure, Fig.11. However, in the case of the Ar/O_2 mixture, t_0 remained almost the same, ~3.5 ns, over the whole range of the tested pressures.

IV. Conclusion

The breakdown parameters of a plasma closing switch with a highly non-uniform field topology developed in the present study have been obtained and analysed. The switch is intended to operate when filled with environmentally friendly gases: the present work provides a comprehensive analysis of the self-breakdown voltages, the time to breakdown and jitter of the switch when filled with air, N_2, CO_2, and a Ar/O_2 mixture.

In the developed switch topology, needle electrodes are mounted on the central trigger electrode. The corona discharges initiated at the tips of these electrodes stimulate the production of charged species including free electrons which helps to minimise the statistical time lag in the breakdown process [32], [33]. In [34], for example, it was shown that the inclusion of a corona electrode helps to reduce the jitter of a spark-gap switch filled with O_2/N_2 mixtures with a range of concentrations of N_2 or with pure N_2 by a factor ~3.6, from 55 ns down to 15 ns. The next objective is to investigate the operating performance of the developed PCS in repetitive regimes: it is expected that corona discharges will provide an improved voltage recovery rate as it was shown in the case of SF_6-filled switch, [35].

It was found that the self-breakdown voltage, V_{br}, increases for all tested gases as the gas pressure increases and they are similar for both positive and negative polarities of dc stress. The obtained functional behaviour of the self-breakdown voltage shows an almost linear functional dependency on the pressure in the case of air and N_2, providing a high degree of predictability in operation of the switch filled with these gases.

However, for the Ar/O_2 gas mixture and for CO_2 the functional dependency of $V_{br}(p)$, demonstrates a non-linear behaviour which is typically observed in electronegative gases in highly divergent electric fields. Corona discharges result in the development of space charge and in shielding of the electric field near the corona electrode(s), [36], [37]. Thus, within a specific range of the experimental parameters (including operating gas pressure), the breakdown voltage increases faster than the corona ignition voltage; the difference between these two voltages provides the corona stabilised regime of operation. However, in some cases, with an increase in the gas pressure above a specific value, the breakdown voltage saturates or even decreases, [26], [38]. As a result, the difference between the corona ignition and breakdown voltages reduces or disappears completely (no corona stabilization regime). This complex phenomenon depends on multiple parameters including the gap topology, gas composition and gas pressure. In the present work, the self-breakdown voltage for the Ar/O_2 gas mixture and CO_2 demonstrated such a non-linear behaviour: for these gases, the maximum V_{br} was achieved at ~7 bar with the measured V_{br} then decreasing at higher pressures.

The standard deviation in the self-breakdown voltage, σ_{Vbr}, is another important parameter which characterizes stability of the breakdown operation of the PCS. It was found that for air σ_{Vbr} increases from 1.6% (at 1 bar) to 5.7% (at 10 bar); for N_2 from 1.5% to 8.8%; and for CO_2, from 2.3% to 5%. For the Ar/O_2 mixture this range is from ~1% to ~3% (except the high value of σ_{Vbr} obtained at 7 bar). These values are comparable to, or lower than, the values of the standard deviation in the self-breakdown voltage, 3% to 4%, reported in [11] for the plasma closing switch filled with SF_6.

It was found that N_2 and the 90%/10% Ar/O_2 gas mixture demonstrated lower self-breakdown voltage as compared with other tested gases, however N_2 and Ar/O_2-filled switch has the lowest standard deviation in the self-breakdown voltage. Therefore, potentially N_2 and the Ar/O_2 gas mixture could provide the most stable breakdown characteristics in the case of operation of the switch in the self-closing regime.

The obtained results show that in the triggered regime of switch operation, the time to breakdown in the case of applied dc stress both, 70% and 90% of the self-breakdown voltage increases as the gas pressure increases for air, CO_2, and N_2. For the 90%/10% Ar/O_2 gas mixture, as the gas pressure within the switch increases, the time to breakdown remains within the range ~31 ns to ~35 ns for all gas pressures, from 1 bar up to 10 bar. Thus, this gas mixture provides high stability in terms of the time to breakdown of the plasma closing switch. It was found that the 90%/10% Ar/O_2 gas mixture also provides the lowest jitter as compared with the other tested gases, jitter as low as ~1 ns was obtained at 10 bar for this gas mixture. It is also important to note that switch jitter decreases as the Ar/O_2 gas mixture pressure increases. Potentially, with further increase in the pressure of the Ar/O_2 mixture in the switch, jitter may be reduced to sub-nanosecond level. Another option that could provide reduction in jitter is an increased magnitude of the trigger impulse which will be studied in future work.

The statistical Weibull analysis of the time to breakdown data demonstrated the general tendencies of the Weibull distribution parameters as functions of the gas pressure. It was shown that the characteristic time to breakdown and the waiting time to breakdown for the 90%/10% Ar/O_2 gas mixture remain almost constant over the whole pressure range, while for the other gases these parameters increase with an increase in the gas pressure. The obtained results will help to identify environmentally friendly gases that could be used in specific practical pulsed power applications and will provide stable breakdown characteristics of PCSs.

References

[1] M. Kristiansen, A. H. Guenther, "Plasma Applications" in Electrical Breakdown and Discharges in Gases, Plenum Press, vol. 89b, pp. 383-414, 1981.

[2] J. Lehr, P. Ron, "Foundations of Pulsed Power Technology", Wiley, IEEE Press, 2017

[3] J. M. Koutsoubis, S.J. MacGregor, "Effect of gas type on high repetition rate performance of a triggered, corona stabilised switch", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 10, pp. 245-255, 2003.

[4] M. Bujotzek, M. Seeger, "Parameter dependence of gaseous insulation in SF_6", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 20, pp. 845-855, 2013.

[5] J. M. Koutsoubis, K.Thoma, S. J. MacGregor, " Electrode erosion and lifetime performance of a triggered corona-stabilized switch in SF_6 at a repetition rate of 1 kHZ", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 23, pp. 1985-1995, 2016.

[6] E. Kynast, K. Juhre, "N_2 and N_2/CO_2 mixture in gas insulated compartments under high pressure" in Gaseous Dielectrics X, Springer, pp. 211-216, 2004.

[7] Y. Qiu, E. Kuffel, "Dielectric strength of gas mixtures comprising", *IEEE Trans. on power apparatus and systems*, vol. PAS-102, no. 5, pp. 1445-1451, 1983.

[8] M. Seeger, P. Stoller, A. Garyfallos, "Breakdown fields in synthetic air, CO_2, a CO_2/O_2 mixture, and CF_4 in the pressure range 0.5–10 MPa", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 24, pp. 1582-1591, 2017.

[9] A. Larsson, "Gas-discharge closing switches and their time jitter," *IEEE Trans. on Plasma Science*, vol. 40, no. 10, pp. 2341–244，2012.

[10] J. R. Woodworth et al., "New low inductance gas switches for linear transformer drivers," *Phys. Rev. ST Accel. Beams*, vol. 13, no. 8, p. 080401, 2010.

[11] A. Larsson *et al*., "Operating Conditions and Switching Delay Time of a Corona-Stabilized Switch During Repetitive Operation", *IEEE Trans. on Plasma Science*, vol. 41, no. 10, pp. 2605–2608, Oct. 2013.

[12] J.-C. Su, B. Zheng, *et. al*., "A voltage-division-type low jitter self-triggered repetition rate switch", *Review of Scientific Instruments*, vol.87, 105118, 2016.

[13] W. Tie, X. Liu, S. Liu, "Low-Jitter Discharge of a Plasma-Jet Triggered Gas Switch at Low Working Coefficients", *IEEE Trans. on Plasma Science*, vol.42, no.6, pp. 1729-1735, 2014.

[14] W. Tie, X. Liu, Q Zhang, "Experimental Study on the Multi-channel discharge characteristics of a multi-plasma-jet triggered gas switch", *IEEE Transactions on plasma science*, vol.43, no.4, pp. 937-943, 2015.

[15] S. Liu, X. Liu, X. Shen, L. Feng, W. Tie, Q. Zhang, "Discharge characteristics of a dual-electrode gas switch triggered by ejected plasma in N_2 and SF_6", *IEEE Trans. on Plasma Science*, vol.45, no.6, pp.969-974, 2017.

[16] Y. Chen, J. Dickens, J. Mankowski, and M. Kristiansen, "Evaluation of a triggered 50 kV, 100 Hz, sub-ns jitter high pressure gas switch with pressure, trigger magnitude and gas temperature," *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 18, no. 4, pp. 975–982, 2011.

[17] A. Larsson et al., "Time Jitter Study of a Corona-Stabilized Closing Switch", ", *IEEE Trans. on Plasma Science*, vol. 40, no. 10, pp. 2646–2652, 2012.

[18] J. R. Beveridge, S. J. MacGregor, M. J. Given, I. V. Timoshkin, J. M. Lehr, "A Corona-stabilised Plasma Closing Switch", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 16, pp. 948-955, 2009.

[19] M. G. Hogg, I. V. Timoshkin, S. J. Macgregor, M. P. Wilson, M. J. Given, "Polarity effects on breakdown of short gaps in a point-plane topology in air", *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 22, pp. 1815-1822, 2015.

Published in IEEE Transactions on Plasma Science, 2018, **DOI:** 10.1109/TPS.2018.2856306

[20] Y. Chen, J. Mankowski, J. Dickens, J. Walter, M. Kristiansen, "Low-Jitter Triggered Spark Gap with High-Pressure Gas Mixtures", *IEEE Trans. on Plasma Science*, vol. 36, no. 5, pp. 2546-2553, 2008.
[21] J. J. Mankowski, J. Dickens, M. Kristiansen, "High voltage subnanosecond breakdown", *IEEE Trans. on Plasma Science*, vol. 26, pp. 874-881, 1998.
[22] Voltage Probe Manual and Data North Star High Voltage, Inc. Rev January 2016, http://www.highvoltageprobes.com/high-voltage-probe.
[23] Instruction Manual P6015A 1000X High Voltage Probe 070-8223-05, https://www.tek.com/high-voltage-probe-manual/p6015a.
[24] L. K. Warne, R. E. Jorgenson, E. E. Kunhardt, "Criterion for spark-breakdown in non-uniform fields", *J. Appl. Phys*., vol.115, 143303 pp.1-8, 2014.
[25] Y.P. Raizer, "Gas Discharge Physics", Berlin, Springer, 1991.
[26] H. C. Pollock, F. S. Cooper, "The effect of pressure on the positive point-to-plane discharge in N_2, O_2, CO_2, SO_2, SF_6, CCl_2F_2, Ar, He and H_2", *Phys. Rev*., vol. 56, pp. 170-175, 1939.
[27] J. Dupuy, A. Gibert, "Comparison of point-to-plane discharges in air and SF_6", *J. Phys. D: Appl. Phys*., vol.15, pp. 655-664, 1982.
[28] M. P. Wilson, M. J Given, I. V. Timoshkin, S. J. MacGregor, T. Wang, M. A. Sinclair, K. J. Thomas, J. M. Lehr, "Impulse-driven surface breakdown data: A Weibull statistical analysis", *IEEE Trans. on Plasma Science*, vol. 40, pp. 2449-2456, 2012.
[29] T. Kiyan, T. Ihara, S. Kameda, T. Furusato, M. Hara, H. Akiyama, "Weibull statistical analysis of pulsed breakdown voltages in high-pressure carbon dioxide including supercritical phase", *IEEE Trans. on Plasma Science*, vol. 39, pp. 1729-1735, 2011.
[30] W. Weibull, "Statistical distribution function of wide applicability," *Trans. ASME J. Appl. Mech.*, vol. 18, no. 3, pp. 293–297, 1951.
[31] "Guide for the statistical analysis of electrical insulation breakdown data", IEC62539, 2007.
[32] Yu. A. Bykov, E. G. Krastelev, "Corona pre-ionized gas switches with an increased lifetime for Marx generator of the lightning test complex", *IOP Conf. Series: Journal of Physics: Conference Series*, vol. 830, 012022, pp.1-6, 2017.
[33] E. I. Antipova, O. S. Belozerova, E. G. Krasteleva, "A High-Current Rail-Type Gas Switch with Preionization by an Additional Corona Discharge", *Physics of Atomic Nuclei*, vol. 79, No. 14, pp. 1619–1624, 2016.
[34] F. Attmann , M. Sack, G. Müller, "Experiments For Reducing The Jitter Of An Over-Voltage Triggered Spark Gap", *IEEE International Pulsed Power Conference*, Chicago, IL, USA, pp.745-748, 2011.
[35] J. A. Harrower, S. J. MacGregor, F. A. Tuema, "Design considerations for corona-stabilized repetitive switches", *J. of Phys. D: Appl. Phys*., vol. 32, no. 7, pp. 790-797, 1999.
[36] I. Chalmers, Y. Qiu, A. Sun, B. Xu, "Extended corona stabilisation in SF_6-Freon mixtures", *J. Phys. D: Appl. Phys*., vol.18, pp. L107-L112, 1985.
[37] N. H. Malik, A. H. Qureshi, "A review of electrical breakdown in mixtures of SF_6 and Other Gases", *IEEE Trans. Electr. Insul*., vol. E1-14, no.1, pp.1-13, 1979.
[38] L. Christophorou, J. Olthoff, D. Green, "Gases for Electrical Insulation and Arc Interruption: Possible Present and Future Alternatives to Pure SF_6", National Institute of Standards and Technology (NIST), Technical Note 1425, 1997.

Yuan Yao was born in Beijing, China. He received the B.Eng. degree in Electronic and Electrical engineering from Beijing Institute of Technology, China, in 2003, and the M.Eng. degree from the Chinese Academy of Sciences (CAS) in 2008. He worked as an Engineer at the Institute of High Energy Physics, CAS, from 2003 to 2016. Currently he is pursuing his Ph.D. degree in High Voltage Technology at the Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow. His current research interests include electrical breakdown in environmentally friendly gases, plasma closing switches, and corona discharges.

Igor V. Timoshkin (M'07–SM'14) received the degree in physics from Moscow State University, Moscow, Russia, in 1992, and the Ph.D. degree from the Imperial College of Science, Technology and Medicine (ICSTM), London, U.K., in 2001.

He was a Researcher at Moscow State Agro Engineering University, Moscow, and then at the Institute for High Temperatures of Russian Academy of Sciences, Moscow. He joined ICSTM in 1997. He joined the Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, U.K., in 2001, where he became a Reader in 2016. His current research interests include pulsed power, transient spark discharges, environmental applications of non-thermal plasma discharges.

Scott J. MacGregor (M'95–SM'14) received the B.Sc. and Ph.D. degrees from the University of Strathclyde, Glasgow, U.K., in 1982 and 1986, respectively.

He was a Pulsed-Power Research Fellow in 1986 and a Lecturer in pulsed-power technology in 1989. In 1994, he became a Senior Lecturer, with a promotion to a Reader and a Professor of High Voltage Engineering, in 1999 and 2001, respectively. In 2006 and 2010, he became the Head of the Department of Electronic and Electrical Engineering and the Executive Dean of the Faculty of Engineering, and has been the Vice-Principal with the University of Strathclyde, since 2014. His current research interests include high-voltage pulse generation, high-frequency diagnostics, high-power repetitive switching, high-speed switching, electronic methods for food pasteurization and sterilization, the generation of high-power ultrasound (HPU), plasma channel drilling, pulsed-plasma cleaning of pipes, and the stimulation of oil wells with HPU. Prof. MacGregor was a recipient of the 2013 IEEE Peter Haas Award. He was an Associated Editor of the IEEE Transitions On Dielectrics And Electrical Insulation in 2015.

Mark P. Wilson (M'10) was born in Stranraer, Scotland, in 1982. He received the B.Eng. (with honours), M.Phil., and Ph.D. degrees in electronic and electrical engineering from the University of Strathclyde, Glasgow, U.K., in 2004, 2007, and 2011, respectively. He is presently based in the High Voltage Technologies research group at the University of Strathclyde, where his research interests include interfacial surface flashover, nanodielectrics, and the practical applications of high power ultrasound, corona discharges, and pulsed electric fields. Mark is a member of the IEEE Nuclear and Plasma Sciences Society, from whom he received a Graduate Scholarship Award in 2011, the IEEE Dielectrics and Electrical Insulation Society, and the IET.

Published in IEEE Transactions on Plasma Science, 2018, **DOI:** 10.1109/TPS.2018.2856306

Martin J. Given (M'99–SM'11) received the B.Sc. degree in physics from the University of Sussex, Brighton, U.K., in 1981, and the Ph.D. degree in electronic and electrical engineering from the University of Strathclyde, Glasgow, U.K., in 1996.

He is currently a Senior Lecturer with the Department of Electronic and Electrical Engineering, University of Strathclyde. His current research interests include aging processes and condition monitoring in solid and liquid insulation systems, high-speed switching, and pulse power.

Tao Wang received the B.Eng. and M.Sc. degrees from Northeast China Dianli University, Jilin, China, in 1993 and 1996, respectively, and the Ph.D. degree from the University of Strathclyde, Glasgow, U.K., in 2005.

He joined the Newland Entech, China, as a Research Fellow, developing high-efficiency industrial ozone generator. He joined the Department of Electronic and Electrical Engineering, University of Strathclyde, as a Lecturer, in 2010. His current research interests include nonthermal gas discharges and their applications in gas synthesis, water disinfection, and advanced oxidation process in water.